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# Selection of battery technology to support grid-integrated renewable electricity

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## HIGHLIGHTS

- ► Renewable electricity places additional strain on the electricity grid.
- ► Grid support services to provide flexibility are becoming more important.
- ► Battery energy storage systems offer a broad range of storage abilities.
- ► Lithium-ion and lead–acid batteries are suitable for short duration services.
- ► Sodium–sulfur and vanadium redox batteries are suitable for long duration services.

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## ABSTRACT

Operation of the electricity grid has traditionally been done using slow responding base and intermediate load generators with fast responding peak load generators to capture the chaotic behavior of end-use demands. Many modern electricity grids are implementing intermittent non-dispatchable renewable energy resources. As a result, the existing support services are becoming inadequate and technological innovation in grid support services are necessary. Support services fall into short (seconds to minutes), medium (minutes to hours), and long duration (several hours) categories. Energy storage offers a method of providing these services and can enable increased penetration rates of renewable energy generators. Many energy storage technologies exist. Of these, batteries span a significant range of required storage capacity and power output. By assessing the energy to power ratio of electricity grid services, suitable battery technologies were selected. These include lead-acid, lithium-ion, sodium-sulfur, and vanadium-redox. Findings show the variety of grid services require different battery technologies and batteries are capable of meeting the short, medium, and long duration categories. A brief review of each battery technology and its present state of development, commercial implementation, and research frontiers is presented to support these classifications.



## 1. Introduction

It is well established that dependence on fossil fuel resources creates vulnerability to price fluctuations in international fuel markets and leads to anthropogenic greenhouse gases causing human induced global warming. With a peak in global oil production likely occurring before 2020, the pressure to use alternative energy sources is greater than ever [1]. Governments around the world are developing aggressive renewable energy and electricity plans focused on increasing the installed capacity of wind, solar, and other intermittent renewable generation devices (e.g. in-stream tidal). Worldwide wind turbine generating capacity grew from 17,400 MW in the year 2000 to 197,039 MW in the year 2010 and continues to show exponential growth rates worldwide [2]. Solar energy is observing similar growth with cumulative global installed photovoltaic capacity doubling since the year 2007 to 39,800 MW at the end of the year 2010 [3,4]. With such rapid growth of these technologies, the implications of high penetration levels of renewable generation must be carefully considered.

To consider the impact intermittent renewable generation has on the existing electricity grid, Fig. 1 gives a time series plot of measured values of electricity demand and several renewable generation types within Nova Scotia, Canada. Electricity demand is the total provincial load on the electricity grid[2]; tidal stream speed is approximated as the time derivative of tide height in the Bay of

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[2] Nova Scotia Power Incorporated. Hourly Total Net Nova Scotia Load. http://oasis.nspower.ca/en/home/default/monthlyreports/hourly_ns.aspx.

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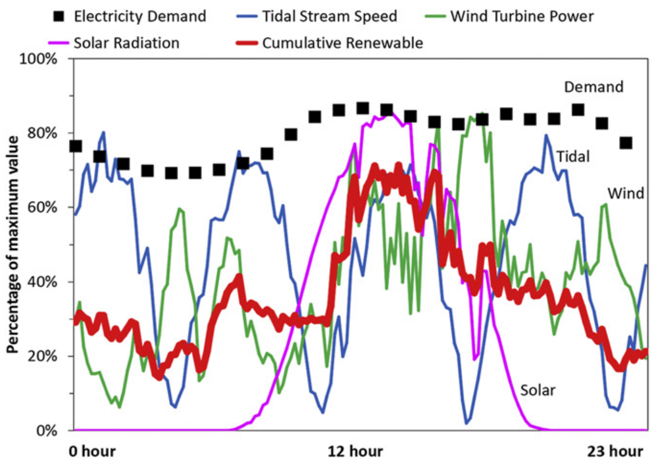


**Fig. 1.** One day profile of electricity demand and renewable generation for the province of Nova Scotia (10 September 2011).

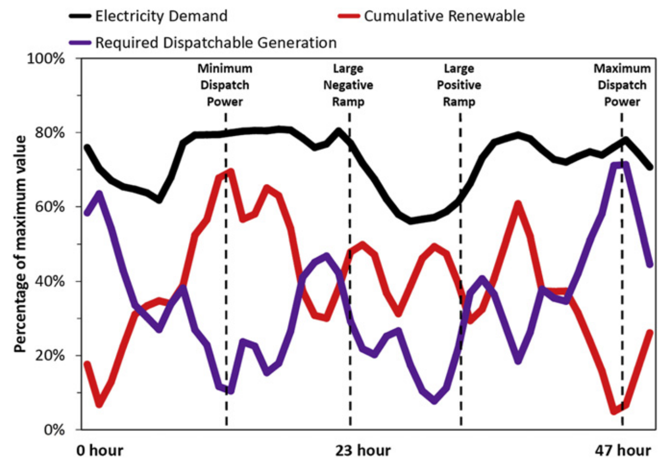


**Fig. 2.** Two-day profile of electricity demand, cumulative renewable generation, and the resultant required dispatchable generation for the province of Nova Scotia (16–17 September 2011).

Fundy[3]; wind turbine power is the output of a single 0.8 MW rated wind turbine in the Cobequid Mountains[4]; solar radiation is the total incident upon a collector inclined 45° and facing due south at Dalhousie University[5]; and cumulative renewable represents the combined output of the three renewable energy types. All values are normalized by maximum monthly value and are based on 10-min averages with the exception of 1 h electricity demand.

Fig. 1 shows electricity demand fluctuating with higher daytime and lower nighttime values. The three renewable resources are distinct with tidal being sinusoidal, wind being stochastic, and solar occurring only during daytime. It is evident from the cumulative renewable profile that using several renewable resources has a smoothing effect, although it does not mitigate peaks or valleys and does not align with the electricity demand.

In addition to the obvious mismatch of renewable resources with electricity demand, there exist operational issues related to fossil fuels being used as backup for high penetration rate renewable generators Fig. 2 shows the required dispatchable generation which is the difference between the electricity demand and cumulative renewable output. This represents the performance requirements of controlled output generators such as fossil fueled thermal units. As noted in Fig. 2, the dispatchable generation must be capable of throttling back to minimum power output while also having sufficient capacity to meet nearly all of the electricity demand. Furthermore, renewable resources may be decreasing while electricity demand is increasing (or vice versa). This requires the dispatchable generation to have positive and negative ramp rate capabilities (i.e. change in power output per unit time) that are significantly greater than would be expected based on electricity demand alone. Conventional steam cycle generators suffer in both regards as they are limited to minimum power output of one-half rated capacity, and ramp rates of 1% per min [5].

In-stream tidal generation is predictable and reasonably consistent, a unique quality of this resource. In contrast, wind and solar renewable resources are such that they respond on timescales of seconds and minutes due to gusts and clouds. Fig. 3 illustrates this characteristic by providing high rate minimum/maximum values recorded during each 10-min timestep. Wind turbine power varies considerably throughout each 10-min period, often ranging from 20% to 95% of the maximum monthly value. In this example the variation of solar radiation is minimal during the morning, but with the onset of afternoon clouds the minimums drop to less than 10%. These brief renewable resource variations may be partially mitigated through the use of geographically separated generators. However, this assumes that sufficient transmission capacity is available within the transmission and distribution electricity grid.

The preceding figures and discussion clearly identify the range of variation in renewable resources corresponding to resource type, influence on conventional generators, and individual renewable generator response. These variations necessitate the use of energy storage if renewable resources are to meet a significant portion of electricity demand without curtailment or fossil fuel backup. There are a variety of options available for both small- and large-scale energy storage systems. Numerous literature reviews compare these various energy storage technologies using several assessment methods [6–13]. Many of these comparison/review articles recommend certain technologies for certain applications and an applicability map is created showing technologies plotted as duration versus power. An example is given in Fig. 4.

The ranges shown in Fig. 4 include installed energy storage projects to the year 2008. The product of duration and power is energy storage capacity, and thus Fig. 4 shows that PSH and CAES

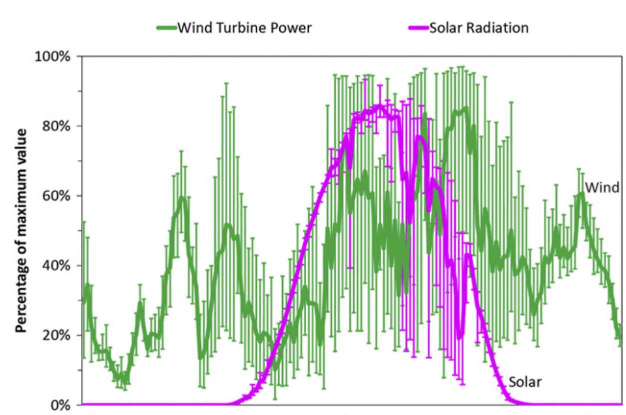


**Fig. 3.** One day profile of 10-min timestep renewable generation with 1-s minimum/maximum values for the province of Nova Scotia (10 September 2011).

[3] Fisheries and Oceans Canada. Saint John Station #65 Tide and Water Level Archive. http://www.charts.gc.ca/twl-mne/index-eng.asp.

[4] Colchester-Cumberland Wind Field Incorporated. Contact Lukas Swan (Lukas.Swan@Dal.Ca) for further information.

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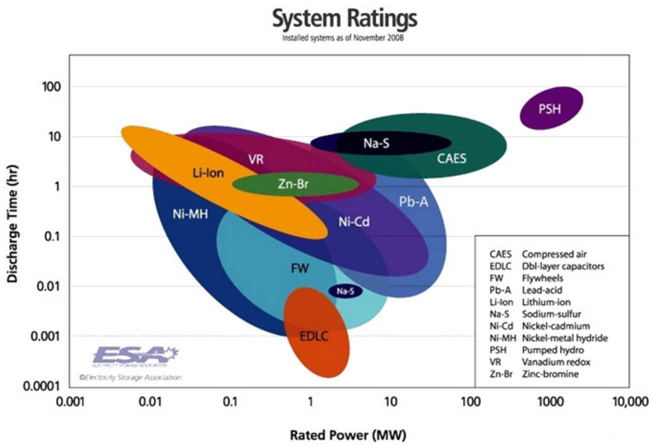


**Fig. 4.** Duration vs. power of energy storage projects as of 2008 [14].

are used in large energy storage projects, FW and EDLC are used in small energy storage projects, and batteries (all remaining abbreviations) are used in medium energy storage projects with extensions into the small and large categories. The unique characteristics of each renewable resource results in different power output variation periods and influence the selection of an energy storage technology.

PHS and CAES are appropriate for long duration energy storage measured in hours or days [10,11,13,15]. PHS is constrained by topography, demanding significant elevation difference and water reservoir volumes. CAES is constrained by geology as it typically stores air in voids created in subterranean salt domes. Both PHS and CAES require large capital investments that deter its application to smaller distributed projects [10,11]. In contrast, supercapacitors and flywheels are applicable to short duration (seconds), high power density applications such a power quality control [10,11,15,16]. Self-discharge of capacitors and flywheels (e.g. frictional losses) render them unsuitable for longer-term energy storage [8,10,11].

Batteries encompass a broad range of duration and power with Pb–A, Na–S, Li-ion, VRB, and nickel-based technologies defining the envelope [9–13,15,16]. As a consequence of the high price of nickel the availability and use of this technology is diminishing. Pb–A, Li-ion, Na–S, and VRB batteries will be the focus of this article due to the broad duration and power ranges available in these technologies.

Section 2 of this article discusses the role that energy storage serves in electricity grid systems. Section 3 describes the selected battery technologies, notable installations with renewable energy, and the forefront of research specific to each chemistry. Finally, the unique characteristics of each battery chemistry are compared with electricity grid services, resulting in selection and justification of a particular technology for each service.

## 2. The role of energy storage

Energy storage systems will play a significant role in the integration of high penetration renewable energy sources. Before addressing the specific roles, it is worthwhile to examine the traditional functions energy storage systems have played in the conventional electric grid. Energy storage systems are already used extensively in many countries for conventional grid support purposes in a variety of applications, with approximately 2.5%, 10%, and 15% of all electricity being cycled through energy storage in the USA, Europe, and Japan, respectively [16].

### 2.1. Energy storage duration categories

Energy storage used for electricity grid services can be broadly grouped into three categories, *short, medium, and long*, based on the duration of its charge/discharge cycle. The principal distinction between the duration categories is the power and energy characteristics required of the storage. The short duration category lasts up to 1 min and is concerned primarily with power quality. This category specifies power characteristics of the storage. The medium duration category spans minutes to hours to compensate for the temporal mismatch between generation and demand. The medium category specifies both power and energy characteristics of storage because it must respond to changes in generation/demand for several minutes or more. The long duration category provides energy wheeling services over periods of hours and days, and as such specifies the energy characteristic of the storage. A summary of services provided by these duration categories is given in Table 1.

The services shown in Table 1 are separated as conventional functions and those to support the integration of renewable energy. The conventional services are primarily to support fluctuations in demand and the limited ramp rate capabilities of centralized generators. In contrast, renewable energy services are to support generation fluctuations inherent to renewable resources and the integration of decentralized generators throughout radially structured electricity grids.

#### 2.1.1. Conventional services provided by energy storage

Conventional services have traditionally been performed by spinning reserve and load-forecasting techniques [17]. The services provided by conventional support technologies allow demands to be met by adjusting power output from flexible generation sources. This support is uni-directional and can only adjust generator output to meet higher or lower demands. Conversely, storage technologies can absorb excess energy or export stored energy thereby providing bi-directional support services. Long-term storage seeks to take advantage of low demand periods by charging the system when generation costs are the lowest and discharging during high price periods for economic gains and grid congestion reduction. It is interesting to note that short- and medium-term services are provided in conventional grids by traditional power quality control methods such as Flexible AC Transmission System (FACTS) devices and spinning reserve [6]; however, no such methods exist to directly take advantage of the long duration services listed in Table 1 other than energy storage devices.

**Table 1**
Energy storage duration categories based upon [6,9,10,16–20].

| Duration category | Conventional services | Renewable energy services |
|---|---|---|
| Short (up to 1 min) | - Angular stability<br>- Voltage stability<br>- Frequency stability<br>- Interruption response | - Flicker reduction<br>- Voltage control<br>- Reactive power control<br>- Resource variation |
| Medium (minutes to hours) | - Spinning reserve<br>- Contingency reserve<br>- Ramp rate compensation<br>- Peak shaving<br>- Transmission and distribution (T&D) upgrade deferral | - Output smoothing/enhanced dispatchability<br>- Demand shifting<br>- Ramp rate compensation<br>- Avoidance of energy production vs. dispatch mismatch penalties<br>- Curtailment prevention |
| Long (hours to days) | - T&D upgrade deferral<br>- Load-shifting<br>- Energy arbitrage | - Enhanced dispatchability<br>- Curtailment prevention<br>- Generation shifting/ Renewable energy arbitrage |

*2.1.2. Renewable energy services provided by energy storage*

Short-term services provide power quality support. Flicker, voltage excursions, and reactive power disturbances from wind turbines or other intermittent sources are examples of such power quality issues. Power quality issues caused by renewable energy generation are best solved by improved power electronics at the location of the power generation rather than large central or smaller distributed energy storage facilities [18,21]. It has also been suggested that using hybrid systems with FACTS devices backed by some amount of energy storage could be used to address multiple duration functions required for energy systems [6,22].

Medium duration energy storage functions include ramp rate compensation, time shifting, and output smoothing/dispatachability. Ramp rate compensation is required as some renewable energy sources display very large swings in output. If the output of a renewable source declines over several minutes there must be enough flexible generation capacity to meet the corresponding demand that will no longer met by the renewable energy source [17]. An example of when sufficient flexible generation was not available during a rapid decline in wind production is found in Ref. [23], during which power production in the ERCOT grid did not meet required levels and very high cost units had to be brought online to prevent massive blackouts and system disruption, all while low cost units sat unused.

Generation shifting and energy arbitrage refer to taking energy generated during high output periods of a renewable energy source to a high-demand or high cost period. This can be done over several hours or days to take advantage of the diurnal demand fluctuations seen in nearly all electricity grids.

During low grid demand and high renewable production the power generated from renewable and base load generators on the grid may be larger than the load. Base load generation is generally slow to respond and cannot produce lower than a prescribed safe operation level based on the generator type (coal, nuclear, oil, etc.). This minimum base load is one of the significant aspects of grid flexibility as referred to in Ref. [17] and ultimately leads to renewable energy generation curtailment. Curtailment of renewable generators is highly unfavorable as the wind, solar, and other renewable resources are essentially free, making the economics of such action unfavorable.

Output smoothing and dispatachability refer to the action of specifying and meeting an output level for a given future time period using predicted output values. The energy storage system enables this by providing a means to source or sink the difference between specified output levels and actual generation. This function serves several purposes. First, it allows a system operator to decide with greater confidence which conventional generators will remain as base or intermediate load. Second, it reduces requirement for spinning and contingency reserve as the non-dispatchable renewable resource now has prescribed dispatched levels that can be given hours in advance. Finally, it protects the grid from rapid swings in output levels from power generated from renewable resources.

Energy storage requirements for renewable energy integration can be thought of in several ways. In Ref. [17], renewable generation is treated as a “negative” demand on the electrical grid because the output is not dispatchable, and therefore behaves more like conventional demand rather than conventional generation. Using this methodology, the remaining demand after subtracting the renewable generation is that which the conventional electricity generators must satisfy. This approach performs well when considering the medium- and long-term energy storage situation, and demonstrates how curtailment and excessive ramp rates are a serious concern when renewable energy is involved. Alternatively, intermittent renewable energy sources can be thought of as non-dispatchable generation that can be coupled with energy storage systems to create a semi-dispatchable, or at least reasonably predictable, output [22,24–26].

For low penetration of wind and other renewable energy sources, grid operation changes are minimal, and integration costs are very low [27]. As a result, the complexity and cost of energy storage systems makes them unnecessary at low penetration levels [17,18,27]. In Refs. [18,28], the costs of implementing wind into the electric grid on a delivered energy basis are listed from several case studies in the USA. The integration costs of wind energy range from 1 US\$ $MWh^{-1}$ to approximately 9 US\$ $MWh^{-1}$ for studies performed with penetration levels from 1% up to 30%[6] and generally show higher integration costs with higher penetration levels. For comparison, average electricity prices in the United States are ~127 US\$ $W^{-1}$ and can be up to twice that in certain states [29] indicating integration costs between 1% and 8% based on penetration level. As the penetration level of wind or other renewable energy resource increases, the conventional methods of dealing with short-, medium-, and long-term generation variability from these resources begin to encounter difficulty and integration becomes more challenging and costly.

In Ref. [17] a flexibility factor is presented as the ability of a grid to ramp down conventional generation to accommodate wind or other variable generation sources. Additional intermittent resources can be added without the need for curtailment during low demand, high renewable generation periods in flexible grids. Energy storage is shown to be a method of increasing this grid flexibility by absorbing otherwise curtailed energy. Various other methods of increasing grid flexibility exist, many of which are of lower cost than energy storage; however, as penetration levels increase these conventional methods cannot provide enough flexibility, at which point energy storage is required to further increase renewable energy penetration. The cost of integration of renewable energy resources increases with penetration level and at a certain level energy storage systems become a viable, and even essential technology. Energy storage will play a vital role as renewable energy penetration levels increase and electricity grids are no longer able to support renewable energy integration using conventional means.

## 2.2. Defining the energy and power relationship required of the storage

With the several types of energy storage systems and the range of requirements for the various services categories, it can be difficult to determine the suitability of a system for a given application. Discharge time of a system is one characteristic that can immediately identify possible options for a given application. By comparing the stored energy quantity and power requirements of the application with the characteristics of the battery technologies, one or more suitable types may be identified. Following this process, battery technologies can be compared on other merits such as cycle life, cost, and efficiency. This energy and power comparison is completed using a figure of merit defined as the ratio of energy to power, $E/P$. The values used in this calculation are based on the maximum continuous discharge rating required of the application (electricity grid service category).

Table 2 presents the $E/P$ ratios required for each service duration category. The calculation accounts for the realities of batteries by defining a battery state of charge (SOC) operating window.

[6] Penetration is defined as the ratio of installed renewable power generation capacity to the total installed power generation capacity in the given electricity grid.

Significant heat is generated during high rate discharge (short category) and can overwhelm the thermal mass of the battery and as such the SOC range is limited to 40%. Medium rate discharge (medium category) is limited to 75% due to heat rejection characteristics of the battery. Low rate discharge (long category) is limited to 80% to preserve battery cycle life and lifetime energy throughput that would be reduced via complete discharges (i.e. 100% SOC range). The required $E/P$ ratio for a given duration is calculated according to:

$$E/P = \text{Duration (hours)}/\text{SOC Range (decimal)} \quad (1)$$

The inclusion of SOC range within the calculation enables an immediate comparison of the requirements with the characteristics of specific battery technologies. This comparison and selection of batteries for specific categories are given in Section 4 based on the characteristics presented in Section 3. The $E/P$ values for each duration are summarized in Table 2 by order of magnitude.

## 3. Battery technologies and characteristics

This section briefly describes the four considered battery technologies including their history, chemistry, existing systems integrated with renewable energy, and present research areas.

### 3.1. Lead–acid (Pb–A)

#### 3.1.1. Overview

Pb–A batteries were first created in the 1860's and are one of the most mature, least expensive and widely used rechargeable battery technologies in the world today. Decades of research and development have been spent on all aspects of the Pb–A battery including plate design, active material composition, electrolyte composition, separator materials, and case design [30]. The defining characteristics of lead–acid batteries include relatively low cost, technological maturity, low energy density, and limited cycle life. The specific values for various characteristics of Pb–A batteries can be found in Table 3.

The basic composition of a lead–acid battery is a metallic lead negative electrode and a lead-oxide positive plate with sulfuric acid solution as the electrolyte. Many additives have been developed for the positive and negative plates which increase cycle life (in the case of antimony) or enhance other desirable properties of the battery such as reduced corrosion or decreased self-discharge [30,31]. The open-circuit potential of the fully charged lead–acid cell is approximately 2.15 V however this value varies with temperature and decreases significantly as the battery is discharged [30]. The following reaction occurs in a lead–acid battery [30].

$$Pb + PbO_2 + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O \text{ (discharge)} \quad (2)$$

**Table 2**
$E/P$ requirements of electricity service categories including a modifier for useful battery operating range.

| Grid service duration category | Duration | SOC range (%) | $E/P$ (kWh kW$^{-1}$) | $E/P$ order of magnitude (kWh kW$^{-1}$) |
|---|---|---|---|---|
| Short (up to 1 min) | 1 s | 40 | 0.0007 | 0.01 |
| | 60 s | 40 | 0.04 | |
| Medium (minutes to hours) | 6 min | 75 | 0.13 | 1 |
| | 60 min | 75 | 1.3 | |
| | 3 h | 75 | 4 | |
| Long (hours to days) | 6 h | 80 | 8 | 10+ |
| | 2 days | 80 | 64 | |

There are two classifications of lead–acid batteries: flooded and valve regulated. There are also a variety of electrode designs including prismatic (flat plate), tubular, and spiral wound. Flooded type Pb–A batteries contain mobile liquid electrolyte with non-restrictive vents to atmosphere, requiring replacement of water due to gassing caused by electrolysis. Valve regulated types allow recombination of the hydrogen and oxygen that evolves during charge completion and overcharge reactions, eliminating the need for electrolyte maintenance. The electrolyte in valve regulated Pb–A batteries is typically immobilized using either advanced glass mat (AGM) or a gel. Pb–A batteries have relatively lower cycle life due to the participation of both active materials and the electrolyte in the reaction, corrosion of the positive plate during overcharge, and the passivation of the negative electrode due to sulfation [31]. As such, lead–acid batteries have seen limited use for heavy cycling applications (such as those seen in many grid support applications) and instead find application in float service or infrequent cycle applications such as uninterruptible power supplies and demand peak shaving. Spiral and tubular type batteries better compress the electrodes which have been shown to increase cycle life through improved cohesion of the positive active mass during heavy cycling [30].

#### 3.1.2. Existing installations

There exist numerous large Pb–A grid connected energy storage systems functioning in various roles around the world. The largest Pb–A system was located in Chino, California and was rated 10 MW, 40 MWh. The system was installed as a demonstration project and performed a large number of services including peak shaving, load leveling, load following, spinning reserve, frequency control, voltage and reactive power control, and black-start operations. The system operated with 72% overall efficiency and used lead–acid cells that were warranted for a minimum of 2000 deep discharge cycles [32,33]. The battery performance met expectations and demonstrated the potential of large-scale Pb–A systems. Another notable Pb–A installation was the 17 MW, 14 MWh BEWAG test facility in Germany used for frequency regulation and spinning reserve applications. This installation provided nearly 7000 times its nominal storage capacity over a 9-year service life [34]. The Puerto Rico Electric Power Authority installed a Pb–A battery sized at 20 MW, 14 MWh which provided spinning reserve, frequency control, and voltage regulation [32]. Unfortunately several of the cells in the PREPA battery bank failed pre-maturely due to inadequate charging resulting from poor measurement and control methods, indicating the importance of appropriate battery management methods [35].

#### 3.1.3. Active research

Despite the accepted classification of this technology as very mature, a wide array of research efforts continue today by addressing limitations in order to make it competitive with other technologies. Areas of research include use of secondary lead through hydrometallurgy production of plates [36], grid alloys [37], advanced models [38,39], charge methods [40,41], battery health monitoring [42–47] and carbon electrode materials for enhanced cycle life [48–52]. Lead–carbon batteries are presently a very active area of research as initial results from lab tests and a limited number of demonstration projects have shown dramatically increased cycle life over conventional lead–acid batteries [53]. Lead–carbon batteries have carbon in the negative electrode in the forms of carbon additive, carbon foam skeleton, or partial carbon electrodes. Initial estimates and tests suggest cycle life during high rate partial state of charge operation of lead–carbon batteries to be 4–5 times greater than a comparable valve regulated battery (12,000 cycles at 10% depth cycles with lead–carbon vs. 2000 cycles

**Table 3**
Battery technology characteristics (based primarily upon [10,11] and/or other sources as noted).

| Battery type | Pb–A | | Li-ion | | Na–S | VRB |
|---|---|---|---|---|---|---|
| | Power cell | Energy cell | Power cell | Energy cell | | |
| Cycle life (cycles @ % SOC variation) | 50 to 200 @ 80% [30], 1000's for shallow cycles [31] | 200 to 1800 @ 80% [13,30] | 3000 @ 80% [13] | 3000+ @ 80% [13] | 4500 @ 80%, 2500 @ 100% [74] | 10,000 to 12,000+ @ 100% [86] >270,000 @ few % [89] |
| Specific energy (Wh kg$^{-1}$) | 30 to 50 [30] | 30 to 50 [30] | 75 to 200 [10,13] | 75 to 200 [13] | 150 to 250 | 10 to 30 [86] |
| Specific power (W kg$^{-1}$) | 300[a] | 75[a] | 2400 [103] | 75 to 300[a] | 150 to 230 possible, commercial ~30 [74] | N/A |
| Energy density (Wh L$^{-1}$) | 50 to 80 | 50 to 80 | 200 to 500 [103] | 200 to 500 | 150 to 250 | 16 to 33 |
| Power density (W L$^{-1}$) | 300 to 400 | 10 to 100 | 4500 [103] | 1500 | N/A | N/A |
| $E/P$ ratio (kWh kW$^{-1}$) | **0.13** | **0.5** | **0.025 to 0.075**[a] | **0.27 to 0.6**[a] | **6** [74] | **1.5 to 6+** [89] |
| Self-discharge per day | <0.5% [13] | <0.5% [13,30] | 0.1–0.3% | 0.1–0.3% | 20%[b] | Negligible |
| Cycle efficiency | 63 to 90% [13,104] | 63 to 90% [13,104] | 80 to 98%[a] [13] | 80 to 98%[a] [13] | 75 to 90% [13,104] | 75 to 80% |
| Format | Cylindrical | Prismatic | Cylindrical | Prismatic | Tall cylindrical | Separate tanks |
| Active material phase | Solid | Solid | Solid | Solid | Liquid | Liquid |
| System level cost (US\$ kWh$^{-1}$) | 200 to 600 | 200 to 600 | 600 to 1200 [13] | 600 to 1200 [13] | 350 | 150 to 1000 |
| Maturity level | Mature | Mature | Commercial | Commercializing | Commercializing | Developed |
| Notable characteristic | Modular | Modular | Sealed, modular | Sealed, modular | High temperature | Flowing liquids |

[a] Based on the authors' laboratory results from testing several different power and energy cells.
[b] Although heat input requirement is ~20% of battery capacity, thermal losses are mostly or entirely counteracted by internal $I^2R$ losses and therefore little to no actual parasitic discharge is observed.

with standard VRLA), potentially making this a promising and low cost technology option for this application [53–57].

Accurate determination of the SOC of Pb–A batteries is an area that continues to see active research. Knowledge of the SOC is crucial to battery lifetime as very deep discharges or excessive overcharges can severely and pre-maturely limit the cycle life of cells [30,31,58]. Only within the last 20 years has sufficient technology become readily available that can use various measurements from the battery to accurately determine the SOC of lead–acid cells. Methods range in simplicity from basic amp–hour counting with charge loss estimation to Kalman filters and neural networks and combinations thereof [42–47]. The most recent implementations of neural networks have been able to estimate the SOC within 2%, while a method using a Kalman filter has shown accuracy within 1% of the actual SOC [44,47]. Many of these methods of SOC determination require significant processing, complex coding, and prior knowledge of the particular physical constants for a given Pb–A cell. This makes implementation of accurate SOC determination very much a custom procedure for each battery system.

## 3.2. Lithium-ion (Li-ion)

### 3.2.1. Overview

Li-ion batteries are a recent technology with roots based at Bell labs in the 1960's and the first commercialization by Sony in 1990 [11]. The defining characteristics of Li-ion batteries are high cycle life, high energy density, high efficiency, and high cost (see Table 3), which have led to their use in small format consumer electronics.

The electrochemical action of a Li-ion battery is different than most types of cells. Charge transfer occurs through ion intercalation rather than chemical reaction of the electrodes. Because overcharge and side reactions are minimal the Li-ion battery can achieve over 90% energy efficiency and nearly 100% Coulombic efficiency [11]. The cathode of a Li-ion cell is commonly made of some form of lithiated metal (M in the following equation) oxide, and the anode is commonly graphitic carbon. The basic intercalation reaction for Li-ion batteries is as follows [59]:

$$yC + LiMO_2 \rightarrow Li_xC_y + Li_{1-x}MO_2, x = \sim 0.5, y = 6\ (\text{discharge}) \quad (3)$$

The roots of Li-ion batteries are in small portable electronics devices, and as such typical storage capacity ranges from 100 to 5000 mAh. These small batteries are not practical for bulk, utility scale energy storage, and several companies have since developed large prismatic type batteries [14]. These larger cells still retain the distinct performance advantages of the smaller cells but are capable of integration with multi-MW systems for grid applications.

The lack of overcharge and side reactions requires the use of complex control circuitry to prevent overcharge which immediately results in overheating and possible failure. Their efficiency enables high discharge and charge currents which increase the risks associated with overcharging [13]. Fortunately, accurate determination of the SOC is possible through various means including amp–hour counting, voltage limits, and others [60–63]. When combined in series each cell or cell grouping must have control circuitry to ensure balance between each cell. This requires reliable and somewhat expensive circuitry, pushing the cost of an already expensive battery even higher [10].

### 3.2.2. Existing installations

The application of Li-ion batteries to grid-scale storage is a recent development. A123 Systems has installed 36 MW, ~9 MWh of grid connected lithium battery systems in various locations serving needs including renewable integration and grid stability [64]. As recently as August 2011, Electrovaya agreed to install a 1.2 MWh lithium battery bank in Ontario for renewable energy integration purposes. Additionally, SAFT announced in August 2011 that it will be providing 3 MWh of lithium batteries for renewable integration in France [14]. Overall, the outlook for lithium batteries in grid applications is very positive as the price continues to decline and the performance is improved.

### 3.2.3. Active research

Li-ion batteries are presently the most actively researched battery technology due to their wide range of potential uses and superior performance to other battery technologies. Present research objectives include reducing production costs, enhancing performance, increasing lifetime, and enhancing safety. These are being implemented by research in cathode and anode materials, electrolyte materials, and manufacturing processes [65,66]. Cathode research is the most common area of research for

commercial batteries and is focusing on replacing the traditional $LiCoO_2$ cathode with materials as $LiFePO_4$, $LiMn_2O_4$ (manganese spinel), $LiNi_{0.5}Mn_{1.5}O_4$ (spinel structure) and other materials for increased energy density, safety, and material availability (cost reduction) [59]. Each new cathode material brings a host of new challenges such as reduced cycle life, voltage differences, incompatibility with existing electrolytes, or other considerations [59,67,68]. Anode material innovation includes use of Li–Sn and Li–Si electrodes for increased specific energy. Unfortunately such anodes suffer from material expansion which is being partially mitigated through mechanical design [59,69,70]. Highly specialized electrodes such as the titanate anode aimed at high rate charge/discharge are in early stages [65,71]. Electrolyte selection is a significant component of overall cell safety with the limited stability range and high vapor pressure of commercial electrolytes being unfavorable. Research is ongoing to identify additives for thermal stability, redox shuttles (to protect from overcharge), shutdown separators (to prevent thermal runaway), and other lithium salts for use as electrolytes [59]. Ionic liquids may be used as electrolytes as they withstand higher overvoltage than lithium salts and are often non-toxic [72,73]. As with other chemistries, accurate determination of SOC remains an objective and recently developed methods can determine it to within 1% of the true value [60–63].

### 3.3. Sodium–sulfur (Na–S)

#### 3.3.1. Overview

Na–S batteries are another relatively new battery technology. Development was seen in many countries starting in the late-1960's through mid-1990's, at which point electric vehicle research programs abandoned it as it was becoming apparent the chemistry was not appropriate for this application [9]. In the 1980's NGK Insulators began work on developing Na–S for grid-scale applications and ultimately developed a grid-scale product that has seen exponential growth rates of implementation related to grid support and renewable energy applications [9,10,74]. Na–S batteries are regarded as one of the lowest cost options for grid-scale energy storage [75]. The defining characteristics of Na–S batteries are high cycle life, high energy density, high pulse power capability, and average to low cost as given in Table 3.

A Na–S battery is constructed with a liquid sodium negative electrode and a liquid sulfur positive electrode. The two electrodes are separated by a solid beta-alumina electrolyte through which only positive sodium ions can pass during charge/discharge. Fig. 5 shows the conceptual schematic of a Na–S battery [74]. The open-circuit voltage of a Na–S cell varies between 1.8 and 2.0 V depending on the SOC [9]. The basic chemical reaction is a combination of positive sodium ions with the molten sulfur according to the following chemical equation:

$$2Na + 2S \rightarrow Na_2S_4 \text{ (discharge)} \qquad (4)$$

There are significant operational considerations with Na–S batteries including the high temperature operation for liquid sodium (300–350 °C) and the high reactivity of sodium with the atmosphere should containment fail [9,11]. If the battery in non-operational, approximately 20% of total capacity is lost daily due to heat loss, requiring energy to maintain the high temperature liquid electrodes [11]; However, if the battery is operating, the inefficiencies provide sufficient heat for the electrode and therefore little or no input energy is required to heat the battery [9].

#### 3.3.2. Existing installations

Na–S battery installations have seen rapid growth in recent years from 10 MW installed capacity in the year 1998 to over 300 MW by 2010 [74,76]. The world's largest battery energy storage system is rated 34 MW, 245 MWh and is installed in conjunction with a 51 MW wind farm for output stabilization [14]. A typical small-scale (distributed energy storage) installation consisting of 1.2 MW, 7.2 MWh is described by Nourai [77]. The detailed project report published by SANDIA National Laboratories (USA) established that installed total system cost is approximately 2500 US$ $kW^{-1}$. This was based on 50 kW, 360 kWh modules each with a cost of approximately 350 US$ $kWh^{-1}$.

#### 3.3.3. Active research

The significant research area for Na–S batteries has been development of a high quality, low manufacturing cost beta-alumina separator with long cycle life capabilities [78–81]. To contend with the high temperature issues all-solid Na–S batteries are under investigation [82,83]. These room temperature Na–S batteries presently display unfavorable cycling characteristics and are not expected to achieve the performance levels of existing high temperature Na–S batteries. Additionally, battery sealing methodologies are an active research area [84,85].

### 3.4. Vanadium redox battery (VRB)

#### 3.4.1. Overview

Development of the VRB began in the early 1980's at the University of New South Wales [11]. VRB cells use $V^{2+}/V^{3+}$ions in the negative half-cell electrolyte and $V^{4+}/V^{5+}$ oxidation states of vanadium in the forms$VO^{2+}$ and $VO_2^{+}$respectively [11]. The defining characteristics of the VRB include extremely large cycle life, independent energy and power construction, low to average energy density, moderate efficiency, moderate cost, and no self-discharge (see Table 3).

Vanadium Redox battery operation is different from that of other batteries because it is a flow battery. In a flow battery two

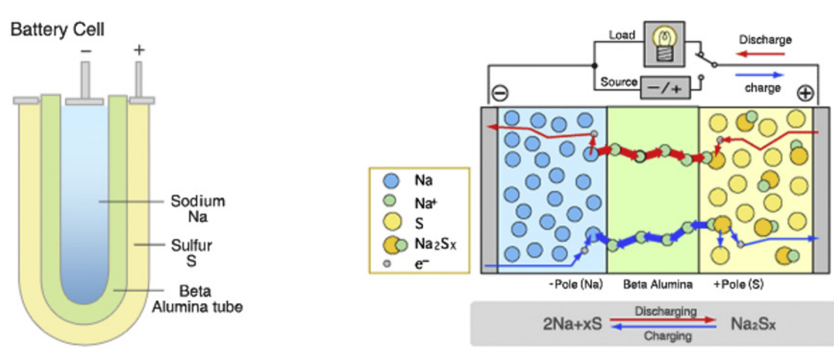


**Fig. 5.** Sodium–sulfur battery schematic [74].

liquid electrolytes are stored in separate tanks to create two separate half-cells. A simple schematic of the VRB can be seen in Fig. 6. The battery operates by circulating the half-cell electrolytes located in separate chambers through to a membrane in which $H^+$ ions transfer, resulting in a redox reaction which creates electrical current.

The result is a battery with 1.4–1.6 V potential which does not suffer from self-discharge [11]. The separate electrolyte storage tanks and reaction membrane decouples the energy and power characteristics of VRB. Increasing the tank size raises the storage capacity but doesn't change power capability. Increasing the membrane area raises the power capability with no change in storage capacity.

A significant issue with the VRB is the limited operating temperature range (10 °C through 35 °C) [86]. This limitation warrants use within a climate controlled environment. Additions to the electrolyte are capable of expanding this range [87].

### 3.4.2. Existing installations

VRB installations are few and small in scale. The largest proposed system to date was announced by Prudent Energy in October 2011, with a capacity of 8 MWh but has yet to be completed and delivered to the customer [88]. The largest existing VRB installation to date was a 4 MW, 6 MWh unit designed to stabilize the output of a 32 MW wind farm [89]. This installation performed roughly 270,000 shallow discharge cycles before it was decommissioned. Many smaller installations exist for a worldwide total of 20 MWh installed capacity used primarily for load leveling, remote area power supply, renewable energy stabilization, uninterruptable power supply, and power quality regulation [10].

### 3.4.3. Active research

In March 2011 a method was discovered to increase volumetric energy density by 70% while also increasing the working temperature range of the battery to −5 °C–50 °C [87]. The VRB is still in its infancy with respect to commercial and developmental maturity, with nearly all aspects of this technology presently under development. The most active research area is design, manufacturing, and use of various separator/membrane materials, as this significant affects power performance and lifetime [90–95]. High ionic conductivity and good resistance to degradation are the key qualities researchers seek for membrane materials. Electrolyte mixtures containing various additives and at varied concentrations yield increased energy density, increased operating temperature range, and reduced production costs [95–97]. Electrode material, design, and manufacturing research focuses on reducing reaction inefficiencies through increased conductivity and surface area of the electrodes [95]. Even basic operational methods such as SOC monitoring, flow rate control and charge–discharge characteristics are still under development [95,98–101]. Models of VRB are also under development to enable specific design to support particular applications [100,102].

## 3.5. Comparison of battery technologies

To select a particular battery type for a given application a multitude of factors must be considered. The most significant factor is the $E/P$ ratio based on the maximum continuous discharge rating of the battery. The ratio of $E/P$ provides discharge time, but will be left in units of kWh $kW^{-1}$ to distinguish $E/P$ using continuous ratings from other non-maximum discharge ratings. Of course the storage could be discharged at a slower rate (increasing $E/P$) although this may not take advantage of the capabilities of the storage.

A selection of battery characteristics, including the $E/P$ ratio (highlighted in bold), is given in Table 3. Pb–A and Li-ion chemistries have been sub-divided into power cells and energy cells, representing the commercially available range. This categorization is provided because it is possible to design both of these batteries for either high specific power or high specific energy through modifications of dimensions of the active material or different anode/cathode materials. In other publications the large ranges are provided to capture these differences; however, this incorrectly implies that the maximum values are achievable for each characteristic in a single battery. In practical application, improving one characteristic (power, energy, or life) often comes at the expense of the other two. Power and energy cell categories were included to capture this tradeoff behavior of a particular cell design.

## 4. Battery technology selection and applications

By comparing the requirements presented in Table 2 ($E/P$ of grid service categories) and the battery characteristics presented in Table 3 ($E/P$ of battery chemistry) the appropriate battery technologies can be selected to suit the various duration categories. Note that the $E/P$ of grid service categories ranges five orders of magnitude (0.0007–64) and the $E/P$ of battery technologies range between two and three orders of magnitude (0.025–6), lying within that of the grid service values.

The comparison of battery and grid service category $E/P$ values is presented in Table 4. There are suitable battery technologies to meet the three-grid service duration categories. However, the minimum and maximum $E/P$ values of the service categories are beyond the capabilities of batteries and thus alternative energy storage technologies such as capacitors (short) and pumped hydro (long) will be required. Only Li-ion power cells meet the short duration category. All battery technologies meet the medium category with Pb–A and Li-ion more suitable for minute-level distributed smaller scale storage and Na–S and VRB for hour-level centralized facilities. This owes both to the $E/P$ characteristics as well as the high temperature and liquid electrolyte storage of the Na–S and VRB technologies, respectively. Regarding long duration category the Na–S and VRB are only suitable for applications less than one day, unless the electrolyte tanks of the VRB are very large.

The battery technologies listed in Table 4 were selected based on maximum continuous discharge capability. Doing so takes advantage of both the power and energy characteristics of the storage. In practice, certain battery systems can provide peaking power for a short period of time. As such a selected system may be able to perform some functions associated with a shorter duration grid service categories. Operating in a hybrid mode maximizes provided services and in some cases a storage system would only be economical if such modes were used [16]. However, these additional capabilities are limited to peak power of the battery. It should be noted that specific battery systems cannot perform services of a longer duration category than for which they were designed. Doing so would fully deplete the system rendering it unavailable (Fig. 6).

Table 4 indicates that multiple battery technologies are suitable for the medium and long grid service durations. Fig. 7 compares two competing battery types in a given duration by providing relative quantities. For example, considering the long-term system characteristics of medium (minutes) duration, Pb–A costs less than Li-ion, but also has less life.

### 4.1. Lead–acid battery applications

Pb–A storage systems operate well on the minute-timescale medium duration grid service category. The low cost and high

**Table 4**
Recommended battery energy storage technologies to meet specific grid services.

| Grid service duration category | Duration | Required *E*/*P* (kWh kW$^{-1}$) | Suitable battery technologies (battery *E*/*P* in brackets) |
|---|---|---|---|
| Short | 1 s | 0.0007 | N/A |
| | 60 s | 0.04 | Li-ion power cell (0.05) |
| Medium | Minutes | <1 | Pb–A energy cell (0.5), Li-ion energy cell (0.4) |
| | Hours | >1 | Na–S (6), VRB (1.5+) |
| Long | 6 h | 8 | Na–S (6), VRB (1.5+) |
| | 2 days | 64 | N/A |

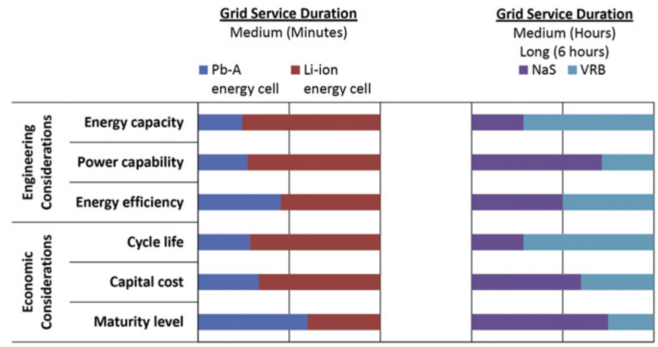


**Fig. 7.** Relative comparison of suitable battery technology characteristics for a given grid service duration.

maturity level of this technology offset the relatively low energy and power characteristics (see Fig. 7), making Pb–A competitive for several applications. However, if frequently deep cycled they will require maintenance and eventually battery replacement. The limited cycle life of Pb–A batteries suggests applications which are called on infrequently (once per day). Note that the *E*/*P* ratio of a grid utility service is independent of its frequency of use. Regarding replacement, Pb–A batteries are highly recyclable, accounting for 70% of the lead used in USA manufacture [105] and therefore have scrap value. The low energy density of the Pb–A battery makes it undesirable for mobile or space limited applications (e.g. cellar of a wind turbine tower). Ideal applications include uninterruptable power supply and short duration grid support to prevent failure or instability that could result in large financial losses [9,11]. The Electricity Storage Association (ESA) states Pb–A batteries are "fully capable and reasonable" for power applications and "feasible but not quite practical or economical" for energy applications [14]. SANDIA National Laboratory along with EPRI has identified several applications and several combination of individual applications for Pb–A batteries in Refs. [16,106], all of which pertain to short/medium duration storage and infrequent deep discharge cycles.

### 4.2. Lithium-ion battery applications

Li-ion batteries possess high power capability, good cycle life, high energy density, and high efficiency; however, they are relatively expensive. The *E*/*P* ratio indicates ideal application in short and medium duration grid services. Li-ion power cell designs are the only suitable technology for second-timescale services. Employing other battery technologies for these purposes would result in dramatic oversizing of the storage capacity. Due to high energy density, portable grid-storage battery banks have been suggested for temporary or semi-permanent application for T&D deferral or other non-permanent applications [71]. The ESA finds Li-ion batteries to fall under the same application category as Pb–A batteries with "fully capable and reasonable" rating for power applications (short duration storage) and "feasible but not quite practical or economical" for energy applications (long duration storage) [14]. However, referring to Fig. 7, it becomes clear Li-ion outperforms Pb–A batteries in all engineering consideration categories, but not maturity or cost. This cost advantage is less distinct than Table 3 would indicate as the Li-ion cycle life is greater than that of Pb–A, and consequently this allows for more energy throughput (i.e. service). Furthermore, the cost of Li-ion is primarily related to storage capacity (i.e. active materials) and less so due to power (i.e. electrical design). As such its use in short duration services is advantageous. Because of these cost and life characteristics, the choice of lead–acid or lithium-ion remains application specific.

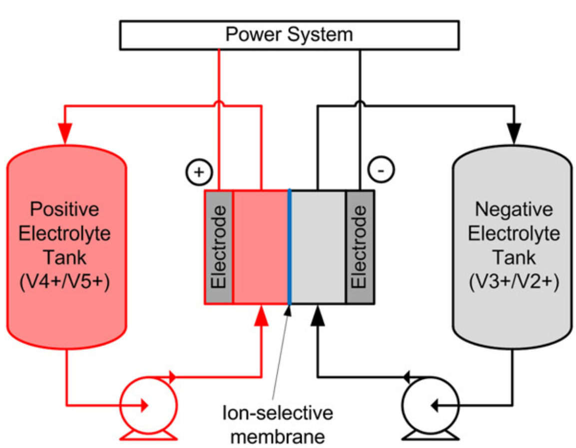


**Fig. 6.** VRB schematic.

### 4.3. Sodium–sulfur battery applications

The *E*/*P* ratio for commercially available Na–S cells suggests its application to hour-timescale medium and long duration grid services. Na–S batteries are the only technology to receive "fully capable and reasonable" ratings from the ESA in both power and energy applications, suggesting this technology will become valuable in grid-storage applications [14]. Due to the high cycle life, energy and power densities, reasonable cost, and benign environmental effects of the battery, Na–S batteries are poised for several energy storage applications [10,11,14]. Unfamiliarity and production capacity (single vendor [14]) will be the limiting factors in deployment of this technology for grid-storage applications. It is evident from Table 4 and Fig. 7 that Na–S has advantages over VRB in the storage duration lasting several hours. Beyond this however, the scalability of VRB gives it competitive advantage.

### 4.4. Vanadium redox battery applications

VRB has relatively low energy density, and small incremental cost for increasing the storage capacity. The *E*/*P* ratio suggests ideal application in medium to long duration storage systems. As it requires sufficient space and maintenance (e.g. pumps) this technology is ideally suited to centralized large-scale long duration storage. Although several VRB demonstration projects are operating, this technology has still not achieved commercial level. The ESA rates VRB (and other flow batteries) as "reasonable" for power applications and "fully capable and reasonable" for energy applications suggesting it could very well fulfill a hybrid role where long duration storage is the primary concern, and power quality improvement is a secondary concern [14].

### 4.5. Distributed versus central energy storage

Ideal placement of energy storage is system specific and models are required to assess the particular benefits of a given placement. Many programs have been developed for simulation of power systems with renewable energy and energy storage systems, of which an excellent review of such programs can be found in Ref. [107]. Excessive transmission of electricity results in increased losses, and therefore storage should generally be located as close to the generation and/or electricity demand as possible. Considering the distributed nature of renewable energy developments and the urbanization of populations, both distributed and centralized storage have value.

Distributed storage has the advantage of placement directly alongside distributed generators to support rural integration, especially within medium-voltage distribution electricity grids. Pb–A and Li-ion batteries are most suitable for this application due to their compact, safe, sealed, non-liquid, zero maintenance, and modular format. This small capacity market will likely not see the use of Na–S or VRB as they either operate with high temperatures, possess liquid connections, or show poor scaling to small storage capacities. In this application the majority of the services will be short and medium duration as they are associated with the medium-voltage grid difficulties.

Central storage has the advantage of economies of scale and dedicated personnel, lending itself to the high temperature Na–S battery and VRB requiring liquid transfer. With increased scale application to medium and long duration services can be achieved. Management of such systems will appear to the system operator like a highly flexible traditional generation source with the added ability to sink power when required. In both the distributed and centralized storage categories communication and control is a critical aspect which will be met with smart-grid technologies.

## 5. Conclusion

The electricity grid services required for renewable integration have been identified and discussed with regards to energy storage systems. Energy storage systems provides a means of increasing grid flexibility and enabling integration of intermittent non-dispatchable generation sources by temporally decoupling this generation from demand. There exists a wide range of storage durations for various integration services and a single technology is unlikely to fulfill all of these roles. Using $E/P$ values of the grid services, several battery technologies were identified and selected on the basis of their own $E/P$ values, after which additional cycle life, capital cost, energy efficiency, and maturity level are considered. It was found that the variety of grid services do indeed demand different battery technologies. Based on this framework the applicable battery technologies for short, medium, and long durations were determined and presented in Table 4. A relative comparison of competing technologies for a particular grid service range is given in Fig. 7.

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